Optical properties of wurtzite structure GaN on sapphire around fundamental absorption edge (0.78-4.77 eV) by spectroscopic ellipsometry and the optical transmission method

G. Yu, G. Wang, H. Ishikawa, Masayoshi Umeno, Tetsuo Soga, Takashi Egawa, J. Watanabe, Takashi Jimbo

journal or publication title: Applied Physics Letters
volume: 70
number: 24
page range: 3209-3211
year: 1997-06-16
URL: http://id.nii.ac.jp/1476/00004488/

Copyright (1997) American Institute of Physics. This article may be downloaded for personal use only. Any other use requires prior permission of the author and the American Institute of Physics.

The following article appeared in Applied physics letters, 70(24), pp.3209-3211; 1997 and may be found at http://link.aip.org/link/?apl/70/3209
Optical properties of wurtzite structure GaN on sapphire around fundamental absorption edge (0.78–4.77 eV) by spectroscopic ellipsometry and the optical transmission method

G. Yu
Research Center for Micro-Structure Devices, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

G. Wang, H. Ishikawa, and M. Umeno
Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

T. Soga
Instrument and Analysis Center, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

T. Egawa, J. Watanabe, and T. Jimbo
Research Center for Micro-Structure Devices, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

(Received 20 March 1977; accepted for publication 15 April 1977)

Spectroscopic ellipsometry (SE) together with the optical transmission method is successfully used to determine the refractive index \( n \) and absorption coefficient \( \alpha \) of undoped gallium nitride film over the spectral range of 0.78–4.77 eV of photon energy. The SE measurement is carried out at an angle of incidence of 60° over the 1.5–4.77 eV energy range and optical transmission measurement over the 0.78–3.55 eV energy range. The refractive index \( n \) and absorption coefficient \( \alpha \) obtained by both methods show unique results in the overlap wavelength region. The measured SE data, \( \Delta \) and \( \Psi \), of the GaN film in the interference part of spectrum are shown in Fig. 1 (dotted lines). We analyze these experimental data using a Sellmeier-type dispersion relationship

\[
\frac{1}{n^2(\lambda)} = A_0^2 + \frac{A_1^2}{\lambda^2 - A_2^2}, \quad k = 0
\]

where \( A_0, A_1, \) and \( A_2 \) are the fitting parameters, and \( \lambda \) is the wavelength of light (in micrometers). The fitted \( \Delta \) and \( \Psi \) spectra, simulated with the best-fit model parameters, which are summarized in Table I, are shown by solid lines in Fig. 1. The thickness (1.25 \( \mu m \)) of the GaN film matches closely with that obtained by scanning electron microscope cross-sectional thickness measurement (1.3 \( \mu m \)). The fit was done with the help of a Sellmeier-type dispersion relationship.
by minimizing the mean-square error $\delta^2$ (unbiased). The excellent fit is found in the wavelength range larger than 400 nm, and the deviations of the fit from the experimental data above 3.4 eV are due to the absorption of light because of the interband transitions.

An optical transmission spectrum of the same sample is shown in Fig. 2. Transmission of the bare sapphire substrate, $T_s$, is also shown in Fig. 2 as the dotted line, which is calculated by using the expression

$$T_s = \frac{2n_s}{n_s^2 + 1},$$

where $n_s$ is the refractive index of sapphire, taken from Ref. 10. As can be seen from Fig. 2, the lowest energy maximum (fourth order) of the interference fringes coincides with $T_s$. Two conclusions can be made from this: first, the absorption coefficient is zero near this wavelength region, second, the roughness of the surfaces on both sides of the sample can be ignored.

The film thickness, $d$, obtained by fitting to the SE data, together with the order $m$ of the interference fringes, is then used to obtain refined values of refractive indices from the relationship

$$\text{TABLE I. Best-fit parameters of GaN on a sapphire substrate determined by SE measurements. The 90\% confidence limits are given with (±).}

<table>
<thead>
<tr>
<th>$A_0$</th>
<th>$A_1$ (nm$^2$)</th>
<th>$A_2$ (nm$^2$)</th>
<th>Thickness $d$ (nm)</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.27±0.02</td>
<td>304.7±7.8</td>
<td>294.0±4.5</td>
<td>1250.2±16</td>
<td>6.2</td>
</tr>
</tbody>
</table>

FIG. 2. Optical transmission spectrum of GaN on a sapphire substrate.

FIG. 3. The optical constants of GaN on sapphire vs wavelength. (a) The refractive indices determined from SE (solid lines) and transmission (data points) compared with data from Ref. 3. (b) The absorption coefficient determined from SE (solid line) and transmission (data points). The expanded figure of the absorption coefficient obtained by SE is shown in the inset.
and are shown by the solid circles in Fig. 3. Using the same thickness of the film, the refractive index spectrum of GaN has also been obtained from SE measurements and is shown in Fig. 3 by the solid line. For comparison, the refractive index spectrum of GaN, obtained from Ref. 3, is also shown in Fig. 3 as a dashed line. The deviation between these two experimental data is about 2\% at 1.0 eV. However, this deviation is within the experimental error of the transmission measurement (2\%) (Ref. 3) and SE.

Using the refractive indices obtained from transmission measurement and the thickness in Table I, the absorption coefficient as a function of wavelength are calculated following the formula of the interference-free transmission ($T_a$) details, which are given in Ref. 9. Figure 3(b) shows the plot of the absorption coefficient versus wavelength obtained by both the SE and transmission methods. The absorption coefficient is much smaller than that given in Ref. 4 in the energy range of 0.78–3.0 eV, indicating that the deep level at ~2.0 eV is not observed in our sample. The nonzero absorption coefficient below the fundamental band may be due to the contribution from the deep level at near 1.0 eV. A free-exciton characteristic structure is observed and is shown in the inset of Fig. 3(a). High-temperature free-exciton luminescence in GaN has also been observed by photoluminescence and photoreflectance spectra. A simple estimate of transition energy of the exciton based on the Lorentzian line-shape functional form is

$$\frac{d^2 \epsilon}{dE^2} = A e^{i\phi}(E - E_0 + i\Gamma)^{-m},$$

where A and $\phi$ are the amplitude and phase of the line shape, respectively, and $E_0$ and $\Gamma$ are the energy and empirical broadening parameters of the transition, respectively. The characteristic parameter $m$ is equal to 2, and describes the nature of the interband excitonic transition. From the numerical fitting of the second derivative of the dielectric function $\epsilon$, with respect to the photon energy using Eq. (4), we found the exciton transition energy at room temperature to be 3.44 eV, in reasonable agreement with the reported result of 3.42 eV, obtained from the modulated photoreflectance measurements and photoluminescence spectra.

In conclusion, we have shown that using an accurate film thickness, which can be obtained by SE, one can determine optical functions of GaN by both SE and transmission methods leading to the same results in the common wavelength region. The free-exciton absorption in the high-quality GaN sample is evidently observed at room temperature, with the transition energy at about 3.44 eV. However, the deep-level absorption near 2.0 eV is not observed.